An Investigation of Fin and Blue Whales in the NE Pacific Ocean using Data from Cascadia Initiative Ocean Bottom Seismometers

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LONG-TERM GOALS

The long-term goals of this project are to develop, evaluate and compare techniques to estimate fin and blue whale locations and densities from ocean bottom seismometer (OBS) data and thus enable the research community to better utilize the increasing number of OBS earthquake monitoring studies near continental margins to understand the distribution and behavior of baleen whales.

OBJECTIVES

Within the seismological community, long-term networks of ocean bottom seismometers (OBSs) are being deployed increasingly for a year or more to monitor earthquakes. These geophysical studies are motivated by the goals of understanding both plate tectonics and the hazards from subduction zones. However, because OBSs typically record signals up to frequencies of ~25 Hz or higher, they also provide a tool of opportunity to monitor the 16-Hz calls of blue whales and the 20-Hz call of fin whales. A number of studies have demonstrated the potential of OBSs to detect and track fin and blue whales (e.g., McDonald *et al.*, 1995; Rebull *et al.*, 2006; Wilcock, 2012).

Within the United States, the Cascadia Initiative represents a major effort to improve our understanding of the Cascadia subduction zone. The National Science Foundation received $10M from the 2009 American Recovery and Reinvestment Act for facilities to support onshore/ offshore studies of subduction zones with an initial 4-year focus on the Cascadia margin. Seventy OBSs are being deployed for a 4-year period from 2011-15 (Figure 1). The experiment maintains an extensive web site (http://cascadia.uoregon.edu/) and is summarized in Toomey *et al.* (2014).

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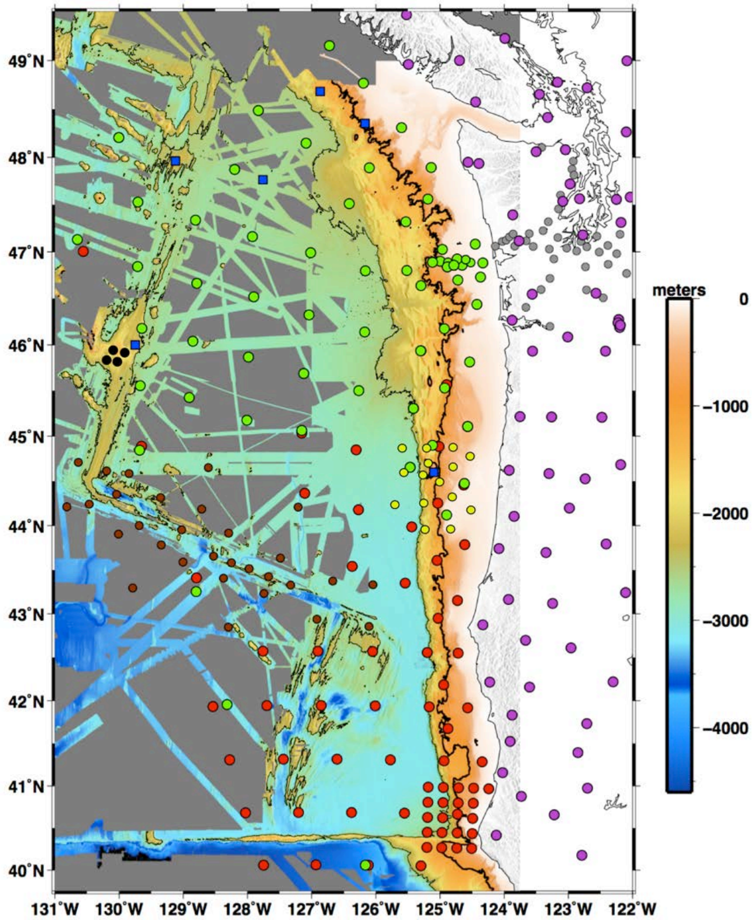

Figure 1. Bathymetric map showing seismometer deployments with color codes as follows: 2011-12 Cascadia Initiative (green); 2012-13 Cascadia Initiative (red) and Blanco Transform experiment (brown); 2007-9 COLZA experiment (yellow); 2007-present Axial Volcano hydrophone deployments (black); cabled OBS (blue); and land stations (purple and grey). Cascadia Initiative deployments for 2013-14 and 2014-15 essentially repeat the deployments for 2011-12 and 2012-13, respectively.

The first three years of deployments (Figure 1) in the northern, southern and then northern halves of the experiment region are now complete (*Toomey et al.*, 2014). A key feature of the Cascadia experiment is that the data are being made publicly available within a few months of the instrument recoveries. Data from the first two years is available from from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) (http://www.iris.edu/ds/nodes/dmc/data) and the third year will be added this fall. Sample rates vary from 50 Hz to 125 Hz with the passband for the 50 Hz data extending to ~22 Hz which is sufficient to record the 20 Hz fin whale calls (centered at 19 Hz in the NE Pacific) and northeastern Pacific blue whale calls (centered at 16 Hz).

The objective of this project is to take advantage of the Cascadia Initiative experiment to develop techniques to study fin and blue whales. To achieve this we will:

1. Implement established techniques to automatically detect fin and blue whale calls on the Cascadia Initiative OBS data

2. Develop an automated method to track blue whales using OBS network data. This will complement the automated method that Wilcock has already developed to track fin whales and provides invaluable data to evaluate techniques to localize whales and estimate density from single OBSs
3. Develop a multipath technique to estimate the location and density of fin whales from a single OBS and systematically compare this to two alternative methods developed recently that are based on total received energy and on particle motions. In shallow water where the fin whale multipath arrivals do not overlap, neither the multipath or particle motion techniques are applicable to estimate ranges so we plan to explore the use of received call amplitudes.
4. Implement and compare techniques to estimate blue whale densities based on received call amplitudes and total received energy and verify them based on call tracks.

APPROACH

1. Detections. Our approach is to apply matched filter and spectrogram cross-correlation fin and blue whale detectors to a subset of Cascadia Initiative data to generate a data set of call detections as a function of time and location across the Juan de Fuca plate. Previously, we have evaluated two methods for automatically detecting fin whales on OBS records: matched filtering and spectrogram correlation. Comparisons of the two methods on test data containing manually identified fin whale calls show that both methods work well with the matched filtering method consistently performing slightly better. To detect blue whale calls, we are implementing a spectrogram cross-correlation detector for Northeast Pacific blue whale "B" calls (*Mellinger and Clark*, 2000). Since this detector has not been used very extensively on OBS data, we must first evaluate its performance with a test data set.

2. *Blue whale tracking*. Previous studies have presented methods to track blue whales based on amplitudes and relative arrival times (McDonald et al., 1995, Stafford et al., 1998; Dunn and Hernandez, 2009; Frank and Ferris, 2011) and have successfully tracked blue whales at ranges up to 40-50 km from the nearest OBS. McDonald et al. (1995) used relative arrival times to constrain the location of blue whales within about 10 km of a local network. At larger ranges they used relative arrival times to constrain the azimuth and variations in the received amplitude to constrain the range based on calibrating amplitudes with airgun data. Dunn and Hernandez (2009) combined handpicked arrival times with a grid search method to track whales within and around a ~100-km-aperture seafloor seismic network in the eastern equatorial Pacific. Frank and Ferris (2011) combined relative arrival time observations and parabolic modeling of amplitudes to track a blue whale in the Solomon Sea. Since the two most recent studies successfully tracked blue whales at distances of up to 40-50 km from the nearest OBS, we think there is a good possibility that Blue whales can be tracked throughout the Cascadia network. Since the previous studies had tracked whales that were largely outside the network, while our study area the blue whales will be enclosed by the network, our initial approach to tracking will be to use relative arrival times and the grid search method following Dunn and Hernandez (2009). While Dunn and Hernandez (2009) hand picked a small data set our approach will be to automate the picking and tracking.

3. *Fin whale density estimation.* We are using two approaches to estimate fin whale densities. First, we will use multipath spacing and received amplitudes to estimate the range of calling whales from single OBSs (McDonald and Fox, 1999). At present our multipath technique assumes a horizontal

seafloor and only determines range but we will investigate methods that make use of seafloor bathymetry to estimate both range and azimuth based on the azimuthal variations in multipath spacing in regions of a sloped seafloor or complex bathymetry. In shallow water (<~750 m) the spacing of multipaths is too small to identify distinct arrivals and so we plan to explore the use of range estimation techniques based on modeling the amplitude of calls. We will also explore the possibility of extracting overlapping multipath arrivals using an autocorrelation method described by Valtierra et al. (2013). Density of calling whales can be estimated using the approach of Marques et al. (2012).

We will also apply the single-hydrophone methods developed by Mellinger, Thomas, Küsel, and others (e.g. Mellinger et al., 2009; Küsel et al. 2011, Helble et al., 2013) to estimate density from total received energy in specific frequency bands. In essence, the method uses whale calling rate and source level, combined with acoustic propagation modeling, to estimate the amount of acoustic energy that would be received at a given sensor from a whale. This is combined with the density of whales in an area and distributions of these parameters (call rate, source level) in a Monte Carlo model to estimate the total energy received as a function of whale population density. The actual received energy is then measured and applied to the inverse of this function to estimate the actual population density for a given time period.

An important component of our study will be an effort to validate our two techniques and compare them with each other and with a third technique based on particle motions developed by European researchers (Harris *et al.*, 2013). Our approach will be to use an extensive data set of existing tracks at the Endeavour area that provide ground truth for estimates based on a single OBS. For the Cascadia data we will start our comparison of techniques with a single OBS in an acoustically simple mid-plate environment and then expand the comparison to consider OBSs in a range of acoustic environments.

4. *Blue whale density estimation*. Because the duration of blue whale calls is too long to separate distinct multipath arrivals, the two alternative techniques for estimating densities from single OBSs are to model amplitudes and to apply the total received energy method described in Task 3. For blue whales the call energy is primarily in the 14-17 Hz band which is sufficiently distinct from the 19-25 Hz fin whale band to support the technique even though the received energy from blue whales is anticipated to be substantially lower than for fin whales. As for fin whales, our approach to comparing the two techniques will be to initiate the comparisons at a single acoustically simple site and the expand them to include a wider range of acoustic environments. The availability of blue whale tracks obtained by Task 2 will provide "ground truth" for the evaluations.

WORK COMPLETED

The project team met face-to-face in Newport in July and have held several teleconferences. Work over the first few months has focused primarily on the first and third objectives. For the initial analysis, we have identified a subset of the Cascadia data, that comprises example of stations in deep water settings with simple bathymetry at a range of latitudes and with both 50 Hz and 125 Hz sample rates. We have worked primarily on objectives 1 and 3

For objective 1, we have successfully implemented automated procedures to download data from the IRIS DMC. At the UW, Michelle Weirathmueller has implemented a matched filter call detection algorithm and successfully applied it to test data subset. OSU has focused on tuning a spectrogram cross-correlation blue whale detector to the 2011-2013 frequency of blue whale calls. Using 125 Hz

data, OSU has compared the amplitude and detection efficiency for the fundamental frequency (ca. 16 Hz) and the 3rd harmonic (ca. 48 Hz).

For objective 3, Michelle Weirathumueller has continued to develop the automated single station multipath ranging method, work that was initiated with a previous ONR grant (N00014-08-1-0523). Recognizing that the reliability of the method is impacted by systematic differences between prediced range-dependent variations in multipath amplitudes obtained from Bellhop (Porter, 1987) and the observed amplitudes, we plan to explore the use of the observations themselves to create an empirical model of amplitude versus range for the detection algorithm. We are also investigating a tendency for the method to mislocate calls within 2-3 km of an OBS in sedimented regions to ranges of zero kilometers. We have created a draft manuscript for eventual submission to JASA on our technique are are in continued discussions with Danielle Harris at St. Andrew's University and Luis Matias at the University of Lisbon and their colleagues to outline a plan to compare our method with a method they have developed to range to fin whales using particle motions measured by OBSs.

RESULTS

It is too early in the project to report extensive results. One interesting side observation from our early work to implement a fin whale detection algorithm is that the characteristic call frequency and pattern of inter pulse intervals (IPIs) has changed in the NE Pacific over the past decade (Figure 2). In 2003-4, four dominant IPI patterns were observed: single frequency (25 s), two dual-frequency patterns (13-25 and 25-30 s), and a more complex pattern that likely resulted from more than two whales calling simultaneously (Soule and Wilcock, 2013). The most common frequency for these calls was 18-19 Hz. For the Cascadia data from 2011-13, both frequency and IPI were significantly different from the earlier dataset, with frequency alternating between 18.5 and 20.5 Hz and IPI alternating between 17 and 19 s (Weirathmueller and Wilcock, 2014). An initial analysis of data from other experiments in the region for the intervening years suggests that this change has occurred gradually. This study potentially has implications for efforts to distinguish fin whale populations based on IPI (Hatch and Clark 2004), particular in the absence of continuous acoustic observations.

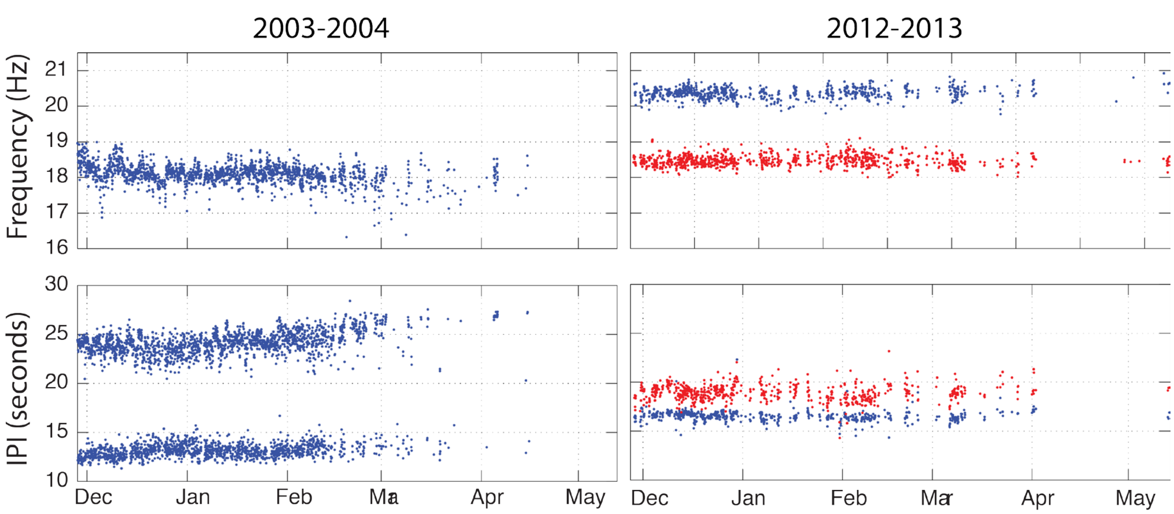

Figure 2. A comparison of frequency and IPI extracted from automatically detected 20 Hz fin whale calls in 2003-4 and 2012-13. Left panels from Keck Endeavour Segment experiment and right panels from Cascadia Initiative instrument G03B

For the blue whale calls, we have noticed that the 3rd harmonic appears to have a lower amplitude relative to the fundamental mode compared with hydrophone observations obtained in earlier years. We are presently determining whether this is an artifact of the instrument response or interaction of the call with the seafloor, or an indication that the amplitude of the 3rd harmonic of NE Pacific blue calls has decreased. To date, all blue whale calls from the Cascadia array contain a strong b-call fundamental (Figure 3); because of this, and because all Cascadia instruments operate in a frequency range that includes the fundamental, we have designed the spectrogram correlation detector using this part of the call (Figure 3).

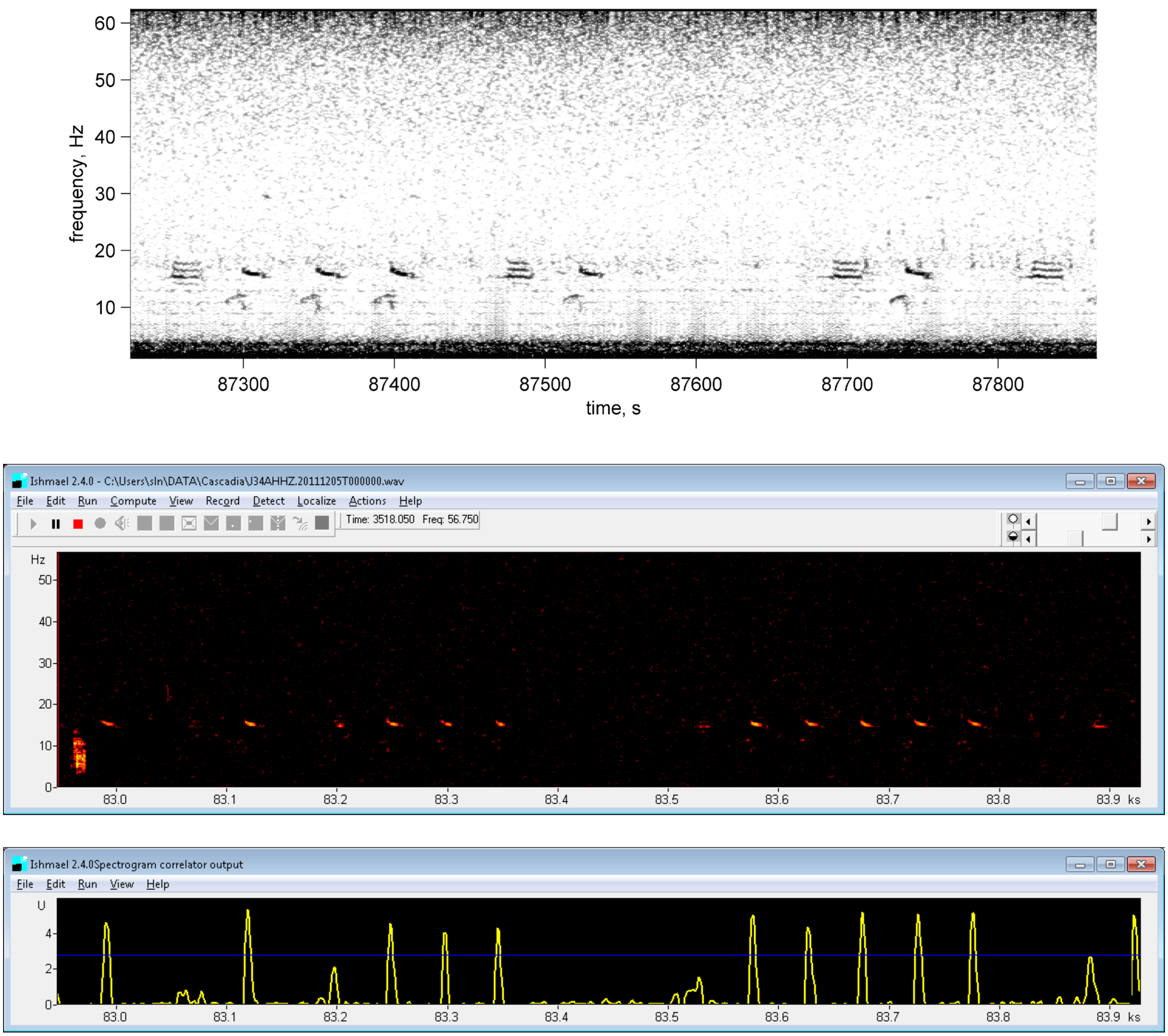

Figure 3 (top) Spectrogram of example blue whale AB call series from Cascadia OBS J34AHHZ (sample rate 125 Hz, window size 512, overlap 75%, 7x padding, Hamming window). Note faint presence of second harmonic and C call but no third harmonic for the B call. (bottom) Example of spectrogram correlation detector running in Ishmael. The top panel is a spectrogram of the data containing a series of blue whale AB calls, while the bottom panel displays the detection function. Each peak above the blue threshold line is counted as a detection of a B call.

Figure 4 summarizes the performance of the single-OBS multipath ranging technique using a test data set from a small OBS network on the Endeavour segment of the Juan de Fuca ridge where ranges are independently determined by tracking. The method works quite well out to ranges of 8 km; for the purposes of using these ranges for density estimation it is be important to develop techniques to minimize the number of calls at larger ranges that are erroneously mislocated to shorter ranges.

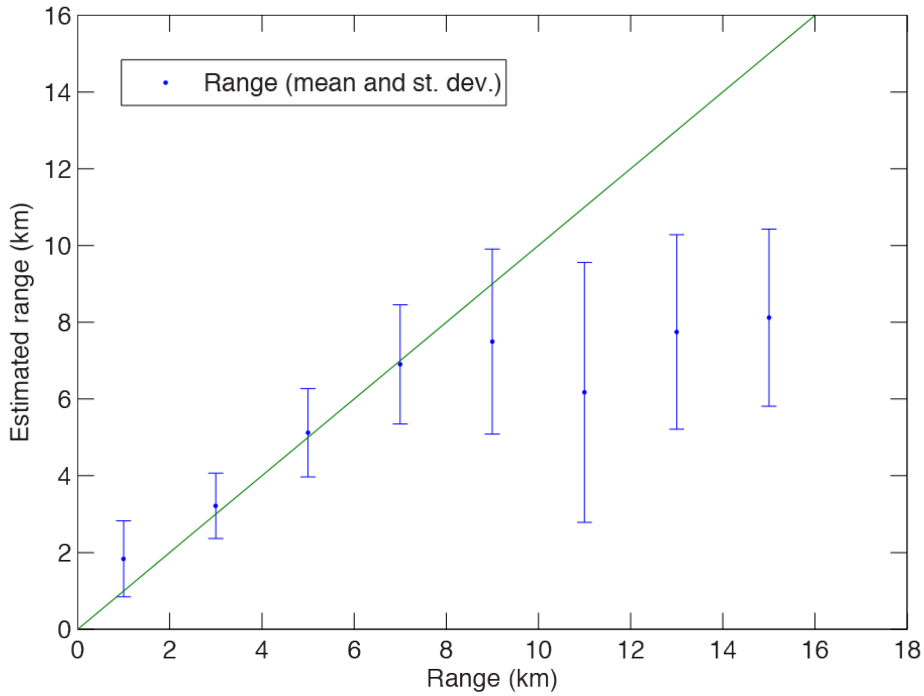

Figure 4. Mean and standard deviation of fin whale ranges obtained from an automatic method to model the relative time and amplitude of multipath as a function of independently derived ranges for a test data set obtained from an experiment on the Endeavour segment of the Juan de Fuca Ridge.

IMPACT/APPLICATIONS

There is a movement within the US and global marine seismic communities to expand the number of ocean bottom seismometers available for earthquake monitoring projects and to undertake experiments with larger footprints and longer durations. The techniques we are developing will allow the Navy and other interested parties to take full advantage of OBS experiments of opportunity in areas that interest them to understand the distribution and behavior of fin and blue whales and potentially other baleen whales if the sampling rate of OBSs are in the future extended to higher frequencies.

RELATED PROJECTS

Wilcock's group previously received ONR funding (N00014-08-1-0523) to use data from a small scale (~10-km aperture) network of OBSs on the Endeavour Segment of the Juan de Fuca Ridge to develop an automated method to track fin whales and understand their distribution. The study at T Endeavour was motivated by the hypothesis that the whales might be found preferentially near the hydrothermal vent fields because these provide a source of food that supports enhanced zooplankton concentrations at all depths in the water column (Burd and Thomson, 1994; 1995). The distribution of calls around the network is non-random, showing high densities near the network and also to the east and northeast and

low densities to the southwest (Soule and Wilcock, 2013). This is consistent with a food source above the ridge that is advected to the east and northeast by the ocean currents associated with the West Wind drift and Subarctic Current. Over 150 fin whale tracks ranging in duration from ~1 hour to 1 day have been obtained and these will be utilized in the work we propose to validate techniques that determine fin whale ranges and densities from single OBSs.

Mellinger and colleagues have received ONR funding (N00014-11-1-0606) for developing a density estimation method for calling fin whales that relies on the total sound energy received at a single hydrophone. The method is being applied to a case study off Portugal and is being compared to a technique that utilizes three-component particle motions to locate proximal whales and estimate density. Both techniques would profit from testing on a different population of whales in a different acoustic environment. The total received energy method can also be applied to calling blue whales and potentially any other species for which there is a frequency band in which call energy rises substantially above background noise. Simpler preliminary versions of this model have already been applied to estimating the population density of fin whales in the mid-Atlantic (Mellinger *et al.* 2009) and leopard seals off the Antarctic Peninsula (Klinck *et al.* 2012).

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